INTEGRATION AND TESTING CHALLENGES OF SMALL, MULTIPLE SATELLITE MISSIONS: EXPERIENCES FROM THE SPACE TECHNOLOGY 5 PROJECT

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ABTRACT
The ST5 payload, part of NASA's New Millennium Program headquartered at JPL, consisted of three micro satellites (~ 30 kg each) deployed into orbit from the Pegasus XL launch. ST5 was a technology demonstration mission, intended to test new technologies for potential use for future missions. In order to meet the launch date schedule of ST 5, a different approach was required rather than the standard I&T approach used for single, room-sized satellites.

The I&T phase was planned for spacecraft #1 to undergo integration and test first, followed by spacecraft #2 and #3 in tandem. A team of engineers and technicians planned and executed the integration of all three spacecraft emphasizing versatility and commonality. They increased their knowledge and efficiency through spacecraft #1 integration and testing and utilized their experience and knowledge to safely execute I&T for spacecraft #2 and #3. Each integration team member could perform many different roles and functions and thus better support activities on any of the three spacecraft. The I&T campaign was completed with ST5's successful launch on March 22, 2006.

1.0 I&T OVERVIEW

The ST5 mission, part of NASA's New Millennium Program headquartered at JPL, consisted of three micro satellites (~ 30 kg each) and was deployed into orbit from the Pegasus XL launch vehicle. ST5 was a technology demonstration payload, intended to test six (6) new technologies for potential use for future space flights along with demonstrating the ability of small satellites to perform quality science. The main technology was a science grade magnetometer designed to take measurements of the earth's magnetic field.

The three spacecraft (S/C) were designed, integrated, and tested at NASA Goddard Space Flight Center (GSFC) with integration and environmental testing occurring in the spacecraft test complex. In order to reach the completion of the development and successful launch of ST 5, the systems integration and test(I&T) manager determined that a different approach was required to meet the project requirements rather than the standard I&T approach used for single, room-sized satellites.

There was insufficient time in the schedule to perform the three I&T spacecraft activities in series as used in standard GSFC I&T approaches. A solution was devised for S/C #1 to undergo integration and test first, followed by S/C #2 and #3 simultaneously. The small size of these spacecraft, each one easily supported by a 4 ft by 8ft table, made the logistical planning for this approach possible. All three spacecraft and their associated I&T support equipment took up less clean room space than that required for one-spacecraft missions. Therefore, all three spacecraft could be physically accommodated at various stages of I&T preparation and execution in the same way as a typical one-spacecraft mission.

Mechanical Ground Support Equipment (MGSE) for spacecraft support and handling were considerably smaller and had less weight requirements than those of larger spacecraft. For some MGSE elements, two or three copies were needed to facilitate the parallel I&T activities and design and analysis efforts were not reduced as a result of the reduced requirements. For other significant I&T aspects, such as personnel staffing, I&T process and schedule, GSE and environmental testing, the increased accommodations of multiple spacecraft outweighed the reductions provided by their smaller size and weight.

In order to plan and execute three spacecraft I&T programs, personnel staffing was seen as the first area having the largest potential for cost growth. Special attention was given to assigning roles and responsibilities through the flow from S/C #1 to #2 and #3. Since S/C #1 I&T and environmental testing was performed first, followed by S/C 2 & S/C 3 I&T in tandem, it was determined that one test conductor team would integrate and test S/C #1, led by the Lead Test Conductor (Lead TC). One electrical technician team and one mechanical technician team would physically

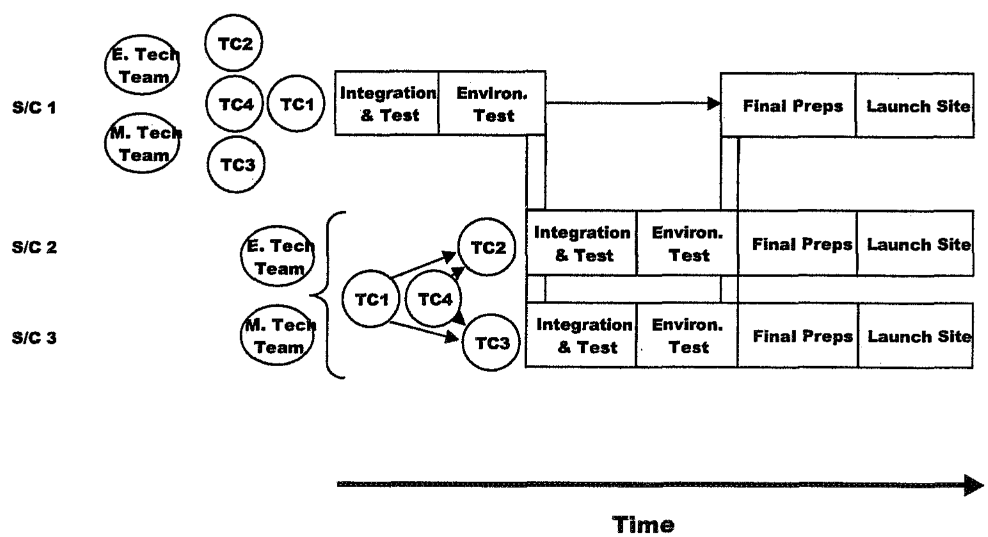

Figure 1.1 I&T flow and personnel perspective

Integrate S/C #1, led by the Lead Electrical Technician. The Test Conductors (TCs) that supported S/C #1 integration and test were then assigned as the Lead TCs for

S/C #2 and S/C #3 integration and test, with the oversight of the overall I&T effort performed by S/C #1 Lead TC, now serving as the Mission Lead TC (Figure 1.1). This enabled the Mission lead TC to perform other duties, such as supporting S/C #2 or S/C #3 activities as needed, or helping the I&T Manager plan future I&T activities. The electrical technician and mechanical technician teams then physically integrated S/C #2 and S/C #3 in tandem, using the knowledge gained from S/C #1 integration, to make S/C #2 and S/C #3 integration more efficient. All personnel were cross-trained within their discipline (i.e. engineer, technician) and were able to serve in multiple roles. At the daily task briefings and biweekly planning meetings, the I&T Manager always kept the team focused to see and work to the bigger picture.

2.0 I&T PROCESS AND SCHEDULE

Economy of repetition was the focus of the I&T documentation and planning process. One set of integration procedures was written for all S/C. Procedures from S/C #1 integration had to be updated, reviewed, and signed prior to S/C #2 and S/C #3 integration. An I&T team member was assigned as responsible for incorporating the red-lines and on-site configuration management support was required to help facilitate order and keep the flow of signatures on track.. It was important to have procedures ready early so that the planned activities could flow along, and there was always a back-up activity ready in case the best laid plans went astray. It was very important to have an dedicated, on-site scheduler for working backup replanning into a new schedule, sometimes more than once a day.

As shown in Figure 2.1, mechanical integration activities were performed on one spacecraft at a time. This enabled efficiencies gained by the repetition of the

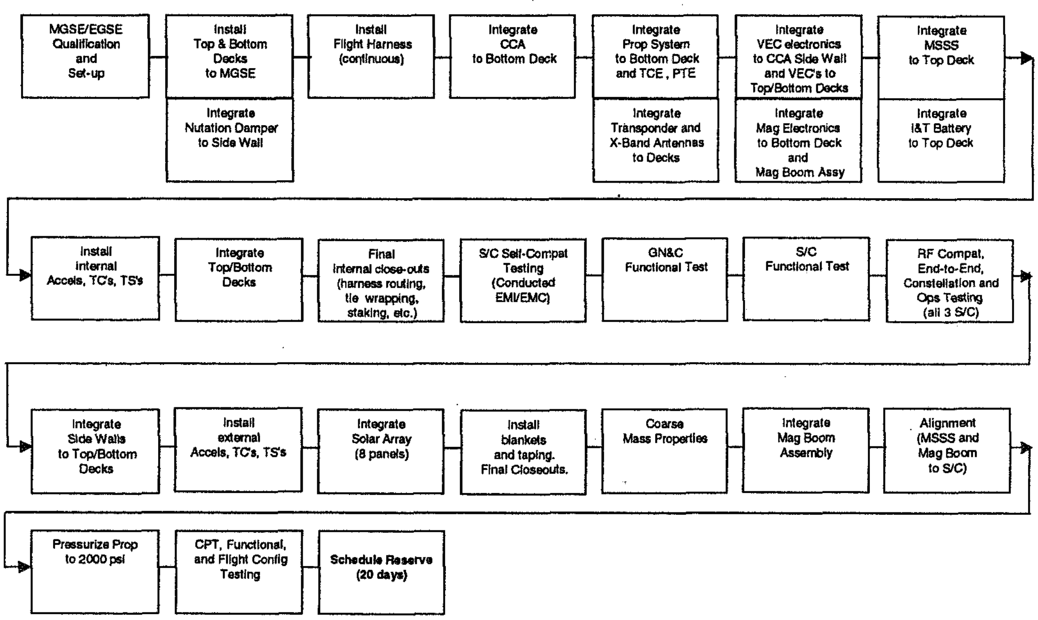

Figure 2.1 ST5 S/C 2 & S/C 3 I&T Flow showing serial mechanical & concurrent electrical activities

activity. Different electrical activities could occur concurrently to S/C #2 or S/C #3. One spacecraft would undergo the electrical integration of one box (ex: sun sensor), while another spacecraft would undergo the electrical integration of a different box (ex: thruster control electronics). When the electrical integration activities involving a particular box was complete, effort would be made to plan a repeat of the electrical integrations of the same box to the other S/C. This allowed the Product Design Lead(PDL), the engineer responsible for a specific subsystem or box, to complete all of his work at I&T at one time. This minimized the time needed to perform the integration to mulitple S/C due to the efficiencies gained through the repetition of the activity. It also allowed the I&T Team and PDLs to compare the integration test data for identically designed units back to back, and more easily notice similarities and differences in the performance of one unit from another. Test procedures were automated, as much as possible, and the same test equipment items, such as oscilloscopes, voltage and current meters, and Break Out Boxes(BOBs), were used throughout integration to keep the test results consistent from S/C to S/C.

3.0 GROUND SUPPORT EQUIPMENT/GROUND SYSTEM

ASIST/FEDS

One ASIST Primary Work Station (PWS) and Front End Data System (FEDS) was used for all three spacecraft to send commands and receive telemetry(Figure 3.1). Command data packets sent from the PWS w/SCID header to the FEDS which removed the SCID header, created a new header using the correct protocol (COP-1) and format (CCSDS), and sent it to the corresponding S/C. Spacecraft telemetry sent

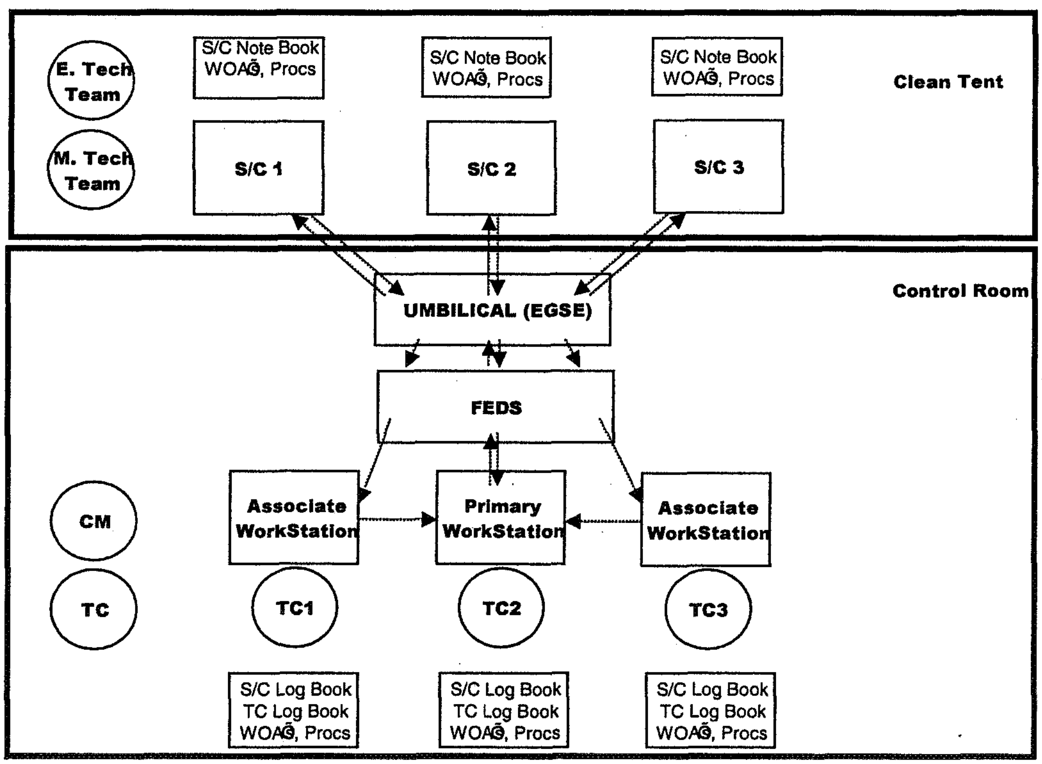

Figure 3.1 ST5 Pictorial Overview of S/C I&T –hardware and personnel perspective

to a separate FEDS input channel for each spacecraft. The data is stored and then sent by the FEDS to the appropriate ASIST Work Station (WS) for display. Each WS was set up to default to a specific spacecraft, and was reconfigurable to maintain flexibility in case of WS failure. A single PWS was used and all commands were routed through the PWS and screened prior to being issued to one S/C. The remaining S/C used an AWS and its commands were routed through the PWS to the S/C. Differences, such as FSW tables and some command sequences, did exist. These differences were handled at the start of a test script where the SCID was used to reference the correct FSW tables, sequences, etc., which were then were loaded. Differences existed in some coefficients (tank pressure, magnetometer current draw, etc.). These were handled at the start of a test script ,where another procedure was called to load the correct specific coefficients.

An umbilical rack was developed which could handle all three S/C. The umbilical Rack allowed for commanding to a specific S/C or broadcast to all S/C. Each Umbilical had three identical sets of hardware and interfaces, one to each S/C. Each set of umbilical rack harnesses was color coded to a specific S/C and he umbilical rack front panel was color coded to a specific S/C. Two RF Racks existed and would interface to one S/C at a time. Three Power GSE Racks existed, each one dedicated to each S/C.

4.0 ENVIRONMENTAL TESTING

Most tests such as electromagnetic interference and compatibility (EMI/EMC), vibration and magnetics performed serially, except thermal vacuum/thermal balance (TV/TB) on S/C #2 and S/C #3. An I&T Team member was assigned as lead for each test. Their responsibility was completing the test plan, test procedure, and heading up the test. Two TV/TB tests were performed, first S/C #1, then S/C #2 and S/C #3 together. S/C #2 and S/C #3 were placed in the same chamber together, but were S/C #2 and S/C #3 independent and had identical test configurations. This allowed independent control, monitor, and test of each S/C. It was easier to build the GSE and physically plan/configure for the test. Only one spacecraft was actively tested at a time, with the other spacecraft in a quiescent state. This allowed for minimal test support and focus on one spacecraft at a time, especially important if problems arose.

5.0 LAUNCH SITE ACTIVITIES

Some activities that typically are performed at the launch site at were performed at GSFC. Propulsion system charging and battery charging performed at GSFC saved time and staffing required at Vandenburg therefore saving travel costs. Similar to flight integration, activities were staggered so that parallel processing could occur and tasks were grouped at the launch site so that required staff for functions at launch site could travel to launch site for a minimum amount of time. Critical flight tests and activities were performed early, such as Comprehensive Performance Test (CPT) and alignment, in the Launch Site flow to know as soon as possible if there was an anomaly that would require specific staffing. Other activities, such as GSE checkout, were performed early when time permitted, even if the item was not needed for some time so that there would be as little activities to coordinate later in the launch site flow. Spare/back-up GSE and hardware were brought out to the launch site, just in case they would be required thus saving the delay in packing and shipping while the launch site team would have been waiting for the necessary item.

6.0 LESSONS LEARNED

In summary, small spacecraft missions create the opportunity to launch multiple spacecraft in the same launch vehicle and operate them as one system. While this provides tremendous advantages to science, it also provides many challenges to engineering. In the field of I&T, many aspects of a campaign can be planed for efficiency and effectiveness relating to multiple, small spacecraft. Having a physical integration layout, in both the clean tent and the control room, that lends itself to multiple integration activities allows for parallel efforts and schedule efficiencies. Cross-training the I&T team to be able to perform multiple roles and functions also enables more I&T operations without doubled or tripled staffing sizes. It was also crucial to have a separate person/team responsible for each spacecraft with authority and accountability. Have an Overall Lead TC, lead electrical technician, and lead mechanical technician who can see the bigger picture and facilitate backup planning. It's also important to assign a person on the I&T Team as responsible for each subsystem including procedures, etc.

High risk testing should be performed early, if possible, to allow finding and fixing problems while there's time in the schedule for resolve them. Perform mechanical activities serially, due to the efficiency gained in the repetition of the activity.

Procedures should be ready to go prior to the start of integration. There is little time to write them once integration starts and it provides more options when re-planning integration activities. A CM person available and dedicated to I&T is especially important when multiple spacecraft are being integrated and red-lines need to be incorporated into the procedures. A dedicated scheduler is essential to work multiple spacecraft planning and re-planning activities. With multiple spacecraft, there is always some activity to complete. Being prepared to work on multiple spacecraft simultaneously means always having a back-up plan and enabling the team to dynamically re-plan.

Automate your test procedures to provide consistent the test results from spacecraft to spacecraft. Have an I&T team member responsible for planning each environmental test. If possible, take one spacecraft through I&T and environmental testing before building and testing more spacecraft to gain efficiencies from learning and repetition.

Use the same test equipment, such as oscilloscopes, meters, and BOBs throughout integration to ensure consistency in the test results from S/C to S/C. Have identical items such as GSE, procedures, harnessing to the greatest extent possible and uniquely identify items, such as harnessing and GSE for a particular S/C. Pay special attention to being consistent.

Develop a physical integration layout, in both the clean tent and the control room, lends itself to multiple integration activities. This layout should be organized to allow for ease of maintaining separate S/C activities.

At the launch site as in flight I&T, perform critical flight testing and activities early so that if problems arise there is sufficient time to fix the problem. Minimize activities at the Launch Site, perform as much work as you can at 'home'.

Plan for slack in the schedule so that the team does not burn out. If efforts get behind, push to catch up to the schedule, then the team can work at a regular pace and feel good. It is a relief, almost like a break, when one S/C's activities are done for a period of time such that the team is only working on one S/C.

As a result of following these practices, the three (3) ST-5 spacecraft were successfully integrated and tested, shipped to the launch site, and ready for launch according to the I&T schedule that was established three years previously.